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Previous Measurements with White and Blue Light.

We have already described measurements of the angular scattering of light from a parallel beam by various samples of distilled, tap, and sea water, the very small scattering observed with distilled water forming a useful check upon possible errors due to extraneous sources of light (2).

The total flux in the beam and the flux scattered per cubic centimetre per steradian at a given angle were both measured by an R.C.A. 931A photomultiplier cell mounted at a suitable distance behind a condensing lens, the mounting being rotatable about a vertical axis passing through the centre of a 12·2 cm. spherical glass flask containing the water to be tested. The beam from a tungsten filament lamp was rendered as nearly parallel as possible in the flask by an arrangement of lenses and diaphragms, and passed centrally through the flask. The optical arrangement is shown in Fig. 1, which is reproduced from the previous paper by kind permission of the Royal Society of London.

With the cell case in position I the photocell would receive a definite fraction of the total flux (calculable from the known dimensions), but this would be far too large, and would instantly destroy the cell. The illumination was accordingly reduced by a combination of neutral filters in the incident beam. As the cell-case was swung out of the beam and through increasing angles of scatter the current fell progressively, and at appropriate angles the filter combination was changed, comparative readings enabling the transmission factors of the various combinations to be found. At large angles of scatter all the reducing filters were removed.

It is evident that the volume of illuminated water "visible" to the photocell decreases as θ, the angle of scattering, increases up to 90°, and for a large range of angles is very nearly proportional to cosec θ. Beyond 90° the volume increases. As shown in our previous paper a consideration of the geometry of the apparatus led us to estimate that we might write $\sigma = 12 \cdot 2\ R \sin \theta$, where σ is the flux per steradian scattered at an angle θ by 1·0 cm.^{3} of liquid illuminated by unit flux

per cm.^{2}, and R is the ratio of the currents obtained in the oblique and straight through positions corrected for all the effects of any reducing filters or galvanometer shunts used.

It is usually more convenient, however, to plot S, the total scattering within a zone 1° wide coaxial with the beam. Evidently $S=2\pi\sigma \sin \theta/57\cdot3=0\cdot110\ \sigma \sin \theta=1\cdot34\ R \sin^2\theta$.

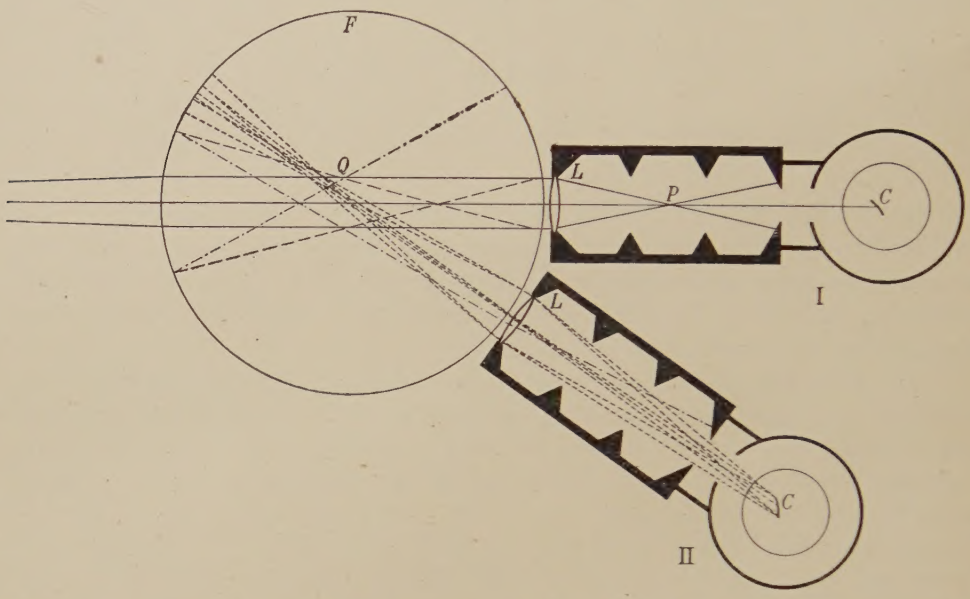

FIGURE 1.—Optical arrangement. The beam enters the flask F from the lamp assembly on the left (not shown). The cell case is shown in two positions : I, as set to measure the direct beam, and, II, as rotated about the centre of F so as to measure the scattered light. P is the focus of the beam formed by the lens L, and Q is the image of C, the cathode of the multiplier photo-cell, formed by the lens L. Q thus marks the minimum cross-section of the ' field of view ' of the cell. The boundaries of the cones of light singly and doubly reflected at the surface of the flask are indicated by broken and chain-dotted lines, respectively.

If we plot S, the zonal scattering, against θ in rectangular co-ordinates the area included between the curve and the θ axis is a measure of that part of the extinction coefficient of the beam that is due to scattering within the range of angles covered.

Unfortunately we cannot include angles near 0° or 180°. For small angles errors may be caused by light scattered by the surface of the flask where the beam enters, by double reflection from these and the exit surfaces, or even by a penumbral effect of the direct beam. For large angles singly reflected light from the exit surface may cause an error even before the cell case commences to cut off the incident beam. For further details reference should be made to the previous paper.

MEASUREMENTS WITH BLUE, GREEN AND RED LIGHT.

The chief object of the measurements described below was to compare the scattering for light of different colours. For this purpose the R.C.A. 931A photocell, which has an antimony-caesium sensitive surface and is predominantly blue-sensitive, was not sufficiently sensitive in the green and the red. It was accordingly replaced by a R.C.A. 1P22 cell having a bismuth-caesium surface. This is more sensitive to white light, and has adequate sensitivity in green and red. It is not as stable as the R.C.A. 931A, but the precautions taken to avoid over-exposure rendered its stability sufficient. The current generated was never allowed to exceed 0·2 μA, and in most series did not exceed 0·1 μA, and, as before, the light was cut off except for the short time needed to read the galvanometer. In many cases a comparatively large reading (for a small angle of scatter) was repeated at the end of the series. The fatigue, if any, was usually found to be negligible.

The colour filters used were 2 mm. glasses made by Schott of Jena—red RG1, green VG2, and blue BG12. Observations with a Unicam spectrophotometer showed that the red cut off sharply at 600 mμ with a high transmission for longer wave lengths, the green had a maximum transmission at 530 mμ falling to 50% of this maximum value at 490 mμ and 570 mμ, and the blue fell to 50% of its 400 mμ maximum transmission at 365 mμ and 455 mμ.

As before Chance-Parsons neutral filters were used to reduce the illumination for small angles or for measuring the direct beam. An improvement on our earlier work was effected by using one ON30 1/100 filter and three ON31 1/10 filters instead of one Wratten 1/100, one ON30, and one ON31. This simplified the procedure for obtaining steps each about 10 times.

The measurements of the colour and also of the reducing filters with the spectrophotometer were kindly made for us by Dr. E. M. Kampa and showed that we could not expect that the neutral reducing filters would have exactly the same transmission for each of the three colours. Moreover we could not expect that the transmission of a combination would be the product of the transmissions of its separate components, except for strictly monochromatic light. Each combination was therefore compared directly with those above and below it in the scale of transparency, and the ratio found for the particular colour in question.

For example, starting with all the reducing filters in and using, say, red light an angle was chosen giving a current which could be multiplied by ten without causing fatigue in the tube during a brief exposure. Filter ON31A was then removed. This increased the current 11·0 times. The angle was then increased until the current could again be multiplied by about ten with safety, ON31A was then replaced and ON30 removed, this increasing the current 13.1 times. The process was repeated for the other two neutral and colour filters. In this way we obtained the factor by which the reading should be multiplied to compensate for the effect of the particular filter combination.

The results are shown in Table 1.

TABLE I.

Filter Combination.	Filter Factor *Blue*	*Green*	*Red*
ON30+ON31A+ON31B+ON31C	131,400	90,000	196,400
ON30+ON31B+ON31C	14,260	10,660	17,870
ON31A+ON31B+ON31C	810	596	1,364
ON31B+ON31C	87	71	124
ON31C	10·7	8·0	9·05
No filter	1·00	1·00	1·00

The figures are the means of several series of tests, which unfortunately showed some variations in the results obtained. The need for restricting the current for the more transparent of the two combinations being compared rendered the current for the denser combination rather small for high accuracy. In view of the enormous range of factors to be covered a greater number of smaller steps might have been preferable, but this would have further complicated the work. It is obvious from the table that in general the reducing filters transmitted most freely in the green and least freely in the red, but there were some rather surprising differences between the effects of different filters.

Another possible source of inaccuracy is the difficulty of measuring θ within about 2°, an error that would cause a large effect on the value of R for the smaller values of θ where the slopes of the curves are very steep. The difficulty arises from the fact that we cannot be sure that the optical axis of the system containing the condensing lens and the photocell coincides with its axis of figure. The photocell cathode is at an angle to the axis, and it is difficult to say whether the effective centre of the sensitive surface is on the axis. For this reason the simplest method of measuring θ is to find by trial the setting in the direct beam that gives the maximum reading, and take this as the zero from which θ is measured. This check was repeated every time that the flask was disturbed for cleaning or to introduce a new sample. The maximum was, however, rather flat, and it was difficult to be sure of the setting to within much less than 2°.

In this connection it is worth noting that the cell receives light scattered by a small region in the centre of the flask within a cone whose optical half-angle is about 8°; θ measures the angle of scattering for the axis of the cone.

CORRECTION FOR INTERNAL REFLECTIONS.

We have, unfortunately, hitherto overlooked a correction for light internally reflected at the surfaces of the flask. This correction becomes very important for angles exceeding about 120°.

Where a ray enters the flask approximately normal to the surface some 4·1% is reflected at the air-glass surface. A little of this is diffusely reflected from the blackened lamp house and constitutes the major source of unwanted light, on which

the magnitude of the effect with distilled water affords a check. Some 0·4% of the beam is also reflected at the glass-water surface, a total of 4·5%. The reduction in the flux is unimportant, as it effects measurements of the direct beam and of the scattered light almost equally. A similar effect is produced at the exit. The effect of the internally light reflected at the exit is important, and must be considered.

Firstly, light is scattered from the direct beam near the centre of the flask at an angle $\theta°$ towards the side remote from the photocell. Of this 4·5% is reflected at the surfaces, and, after passing again through the central region, emerges from the " near " side making an angle $(180—\theta)°$ with the direct beam.

Secondly, 4·5% of the direct beam is reflected at the exit pupil and brought to a focus half-way between the surface and the centre of the flask. From this it diverges as shown in Fig. 1, forming a conical beam of optical half-angle about 15°. The field of view of the photocell thus includes parts of this cone in which reflected rays have azimuths ranging from 165° to 195°, the mean azimuth being 180°. If the cell case is set with its axis at an angle $(180—\theta)°$ it will receive axially rays which, after reflection have been scattered through angles between $(\theta—15)°$ and $(\theta+15)°$. As however the flux reaching the cell includes light scattered within a cone having about 8° half angle the total range of reception is from $(\theta—23)°$ to $(\theta+23)°$. The flux will depend on the mean value of S over this range, and as the curves representing the variation of S with θ are concave upwards it will exceed that found by taking the value of S corresponding to the mean angle θ.

Disregarding this error we should, from the reading at $(180—\theta)°$, deduct 9% of the reading at $\theta°$, i.e. 4·5% to correct for the effect of light which has been scattered through $\theta°$ and then reflected, and 4·5% for that due to light which has been reflected and then scattered through $\theta°$. As we know that this would be too small a correction we have, in presenting the results, simplified the arithmetic by increasing the correction factor to 10%.

The correction is of minor importance for moderate angles, rising to 10% at 90°. For larger angles it increases rapidly, especially in sea water. Thus for sample J the correction for red light rose to nearly 80% of the reading at 140°. This means that for such water little reliance can be placed on the accuracy of the results obtained for angles exceeding 120°.

The correction at these large angles is much less in distilled water or collodion-filtered sea water, as the relative variation of S with θ is much less.

RESULTS.

Two series of experiments were made, the first (samples A to I) in March and early April 1953, and the second in June 1953. Table 2 shows the values obtained for $S45$ (the mean of the three values of S for angles 40°, 45°, and 50°) and $S90$ (the mean for the angles 85°, 90°, and 95°). S is as before the flux scattered within a zone 1° wide co-axial with the incident beam by 1·0 cm^3 of water transversed by unit flux per cm.^{2}. Particulars of the samples tested are given at the foot of the

TABLE 2.

	S45			S90		
	Blue	Green	Red	Blue	Green	Red
March Series	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$	$\times 10^{-7}$
A ...	80·7	70·8	76·2	19·2	16·0	16·9
B ...	—	60·3	—	—	12·6	—
C ...	—	70·5	—	—	16·0	—
D ...	13·5	9·0	10·6	5·7	2·7	2·2
E ...	4·3	3·0	2·8	3·2	1·7	1·8
F ...	45·0	35·6	59·2	11·4	7·8	8·8
G ...	2·4	1·2	1·1	1·6	0·9	0·7
H ...	8·9	5·7	7·2	3·1	2·1	2·1
I ...	2·5	1·2	1·4	2·0	0·8	0·7
June Series						
J ...	69·5	47·6	54·4	15·9	10·5	9·9
K ...	6·4	3·8	4·5	3·2	1·0	1·9
L ...	3·5	2·2	2·0	3·2	1·0	1·1
M ...	2·1	0·9	0·8	2·1	1·1	0·5
N ...	3·2	2·6	2·2	2·0	1·2	0·9
O ...	27·0	20·7	25·0	7·3	4·7	4·7

MARCH SERIES.

A. Surface sea water collected at E1, 16/3/53, tested 17/3/53. (Figs. 2, 3, and 4).

B. Water A, test repeated 18/3/53 after standing in flask undisturbed.

C. Mixed sea water from depths 15-70 m. collected E1, 16/3/53, tested 18/3/53. (Fig. 2).

D. Sample C after standing in flask undisturbed from 18/3/53 to 25/3/53, when it was tested again. (Figs. 2 and 3).

E. Surface sea water collected at E1, 25/3/53, filtered through collodion filter, average pore diameter 1·35μ. Tested, red and green 26/3/53, blue 27/3/53.

F. Laboratory stock of No.11 Berkefeld-filtered off-shore sea water, tested 16/3/53. (Fig. 2).

G. Doubly glass-distilled water poured into flask, tested 1/4/53. (Figs. 2, 3, and 4).

H. Water G through 1 litre of which 2 l. of air had been bubbled on the laboratory roof on Plymouth Hoe at 6.30 p.m. 24/3/53, a foggy evening with wind off the sea and no local contamination. Tested green 25/3/53, red and blue 26/3/53.

I. Doubly distilled water, the second distillation being direct into flask, tested 1/4/53.

JUNE SERIES.

J. Surface sea water collected at E1, 8/6/53, tested 17/6/53. (Figs. 3 and 4).

K. Water J filtered through collodion filter average pore diameter 1·40μ. Tested 17/6/53. (Fig. 4).

L. Water K re-filtered through collodion filter average pore diameter 0·5μ. Tested 18/6/53.

M. Water L filtered (for a third time) through collodion filter average pore diameter 0·1μ. Tested 19/6/53. (Fig. 4).

N. Laboratory supply of distilled water. Tested 19/6/53.

O. Water J 50%, water N 50%. Tested 17/6/53.

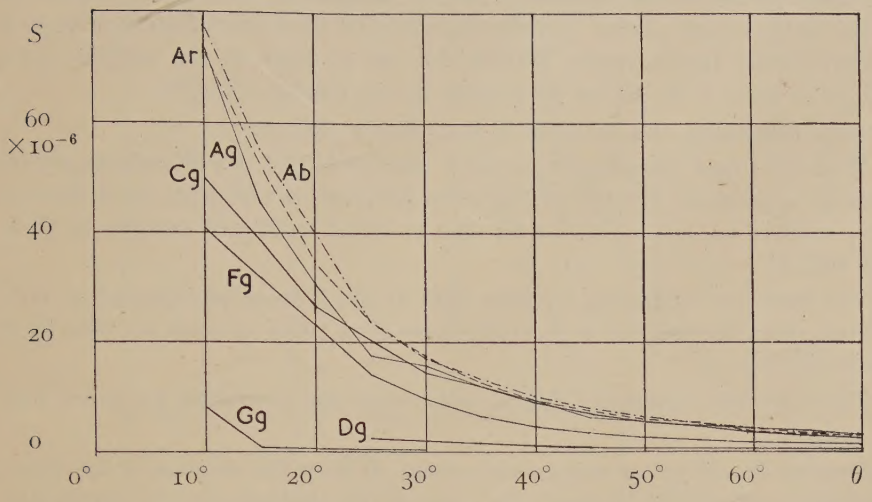

FIGURE 2.

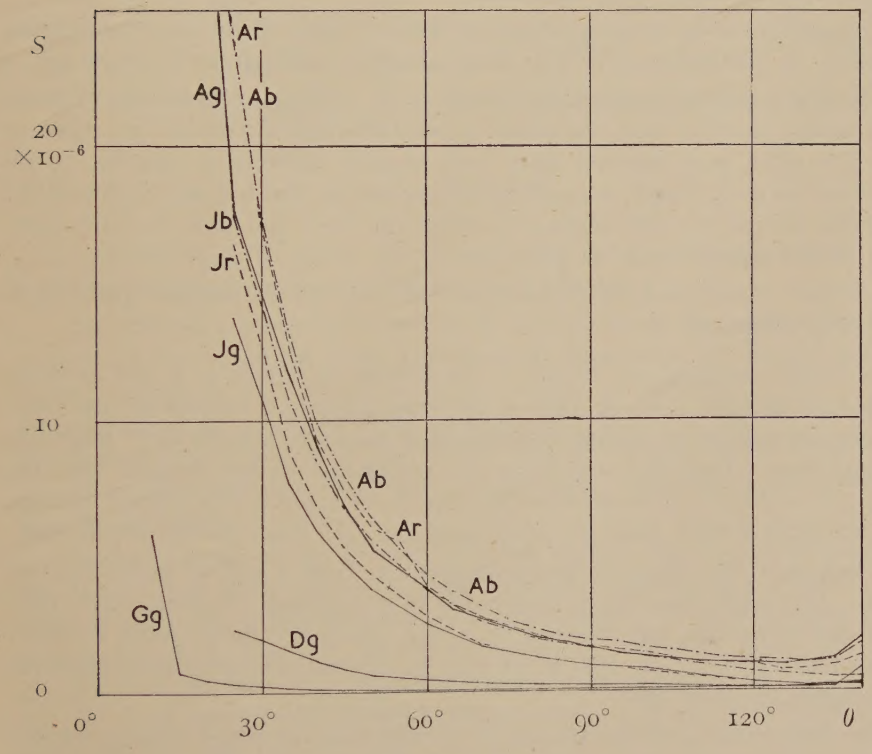

FIGURE 3.

table. Except in the case of samples B and D, samples of sea water were always well shaken before being poured into the experimental flask immediately prior to a test. International Hydrographic Station E1, where most of the samples were collected, is 10 miles S.W. of the Eddystone in the English Channel.

We may summarise the contents of the table as follows :

(1) With the single exception of sample F (Berkefeld (No. 11) filtered sea water) S_{45} is always appreciably greater for blue than for green or red light, the difference being very marked in the case of the distilled or collodion-filtered samples E, G, I, K, L, M and N.

(2) The increased scattering by blue light is much more pronounced at 90°, and for very clear samples S_{90} is generally more than twice as great for blue as it is for green or red.

(3) There is little significant difference between the scattering for green and that for red.

(4) Samples B and, to a much greater extent, D show the clearing of the water due to standing undisturbed, F shows that most of the scattering matter apparently passed a Berkefeld filter, and E, K, L, and M show how it is removed by collodion filters of different average pore diameters.

(5) Sample H shows the great effect of clean air fresh off the sea in increasing the turbidity of distilled water. This is in agreement with Jerlov's results (4).

(6) Sample J scattered appreciably less than A. This is in agreement with our previous results showing that the water is generally less turbid in June than in March. The effect may however have been slightly affected by clearing of the water during the much longer interval between collection and testing, in spite of the fact that the sample was well shaken up before the test ; but there is much other evidence (1) for clearer water in June.

(7) Sample O scattered rather less than the mean of the samples J and N of which it was composed.

More details are given for several of the samples in figures 2, 3, and 4, which are plotted on different scales in view of the wide range of S covered by the tests. The graphs are plotted by joining the individual readings, usually at 5° intervals, by straight lines. They bear the letters corresponding to the samples with the letters b, g, or r added to show whether they refer to blue, green or red light. Graphs for blue are chain dotted, those for green unbroken, and those for red interrupted.

The figures further illustrate the results given in Table 2 and the points referred to above. They show in addition that S fell to a minimum at about 120°—130°. In the March series this was followed by a rise, which became so rapid at about 135°, even for distilled water, that it can only be attributed to some hitherto undiscovered source of stray light.

In the June series S, when corrected for the reflection error, showed approximate constancy up to about 145° to 150°, when, as before, the sudden rise set in. It

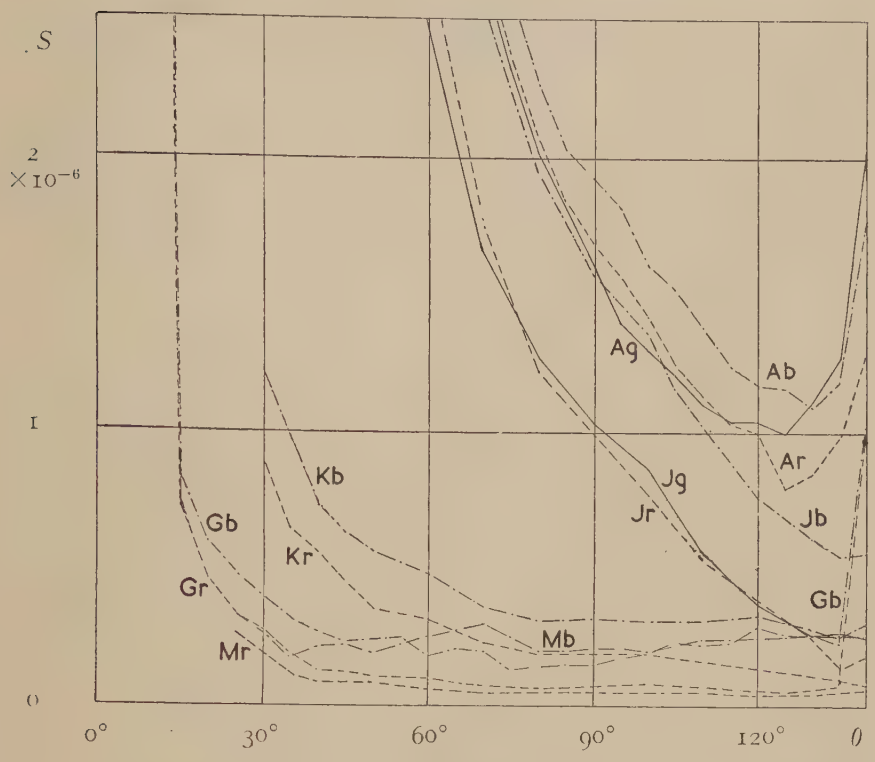

FIGURE 4.

seems possible that in setting up the apparatus for the June tests there was some slight improvement in the adjustment of a curtain.

The difference between the results in the two series, the sudden rise occurring at 135° even with distilled water, and the great importance of reflected light at these angles, combine to cast doubts on all the results for angles over 120°, but do not seriously affect the reliability of the measurements at smaller angles. As the scattering through large angles is of considerable interest we hope to make certain modifications in the apparatus which may improve the reliability of the results in this part of the range.

As pointed out above the area included between one of the curves and the θ axis is a measure of the part of the extinction of co-efficient of a parallel beam that is due to scattering within the range of angles covered. We find in this way that for surface sea water sample A the loss per meter by scattering within the range 25° to 135° was 0·051 for blue, 0·044 for green, and 0·049 for red. This does not include the very large scattering occurring at angles less than 25° or the possibly appreciable scattering at angles exceeding 135°, as measurements in these angular ranges were unreliable or even impossible with our apparatus.

There is little significant difference between the scattering of the three colours as shown by the above figures. This is due to the fact that most of it takes place through the smaller angles, where, as the curves show, the differences are small.

The above figures are intermediate between some given in our previous paper (2) for different samples of sea water tested without colour filter. As pointed out there total loss by scattering, which we would find if we could cover the whole range from 0° to 180°, is more closely related to the extinction co-efficient as found by the Pulfrich photometer than to the vertical extinction co-efficient found from submarine daylight measurements.

Comparison with Hulburt's Work.

It is interesting to compare the above results with those obtained by Hulburt by a visual method (3). He found that for distilled water which had stood undisturbed for several weeks, and using tungsten light, the value of σ for distilled water perpendicular to the beam was $1{\cdot}44 \times 10^{-6}$, the corresponding value of S being $1{\cdot}58 \times 10^{-7}$. The mean value of S for four samples of distilled water recorded in our previous paper and now corrected for reflection error was $1{\cdot}56 \times 10^{-7}$ for tungsten light, while the means of two samples of doubly distilled water now tested with colour filters was $1{\cdot}8 \times 10^{-7}$ for blue, $0{\cdot}85 \times 10^{-7}$ for green, and $0{\cdot}7 \times 10^{-7}$ for red. The two very different methods thus gave reasonably concordant results for the scattering through 90° by distilled water, as Hulburt also found a marked increase in scattering with decrease of wave lengths for distilled water and for "coastal Gulf Stream" water but not for water from Chesapeake Bay. He found the same great increase in scattering for moderate angles, but the shape of his curves differs somewhat from ours. He did not find any increase for angles exceeding 120°.

We desire to express our thanks as follows:—To the Government Grant Committee of the Royal Society, London, for grants covering the electrical apparatus; to the Marine Biological Association of the United Kingdom for laboratory facilities, the use of its ships, and assistance from its Staff at Plymouth as specified in our earlier paper. From this we have reproduced figure 1 by kind permission of the Royal Society, to whom we are further indebted for the loan of the block.

Summary.

(1) Experiments on the angular scattering of white and blue light by samples of sea water and distilled water (2) have now been extended to cover also green and red light. This has been rendered possible by the use of a R.C.A. 1P. 22 photomultiplier cell in place of the R.C.A. 931A used previously.

(2) Allowance is now made for a previously unnoticed correction needed to eliminate the effect of light scattered internally at the surfaces of the experimental flask. This correction becomes important for angles of scatter exceeding about 120°.

(3) Blue light is in general more scattered than either green or red. In sea water the difference is scarcely significant for small angles but becomes appreciable for angles near 90°. For distilled water or collodion-filtered sea water blue is more scattered than green or red at all angles, the difference being very marked near 90°.

(4) There is little significant difference between green and red in any water tested.

(5) The previous results showing that zonal scattering falls to a minimum at about 120° are confirmed, but the reflection correction becomes so important that the reality of the rise observed for larger angles is somewhat doubtful. A sudden rise setting in at angles varying from 135° to 150°, even for distilled water, must be attributed to some as yet undiscovered source of light.

(6) Successive filtering through collodion filters of average pore diameter $1{\cdot}4\mu$, $0{\cdot}5\mu$ and $0{\cdot}1\mu$ rendered sea water at least as limpid as the best doubly distilled water. This is evidence that scattering by particles less than $0{\cdot}1\mu$ in diameter is unimportant in sea water.

(7) The results show a general agreement with those obtained by Hulburt using a visual method.

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